11.2 Types of Chemical Reactions

Guide for Reading

Key Concepts

- What are the five general types of reactions?
- How can you predict the products of the five general types of reactions?

Vocabulary

combination reaction
decomposition reaction
single-replacement reaction
activity series
double-replacement reaction
combustion reaction

Reading Strategy

Outlining As you read, make an outline of the most important ideas in this section. Use the red headings as the main topics and the blue headings as subtopics. Add a sentence or a note after each heading to provide key information about each topic.

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For: Links on Reaction Types
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Connecting to Your World Often charcoal briquettes provide the heat for barbeque grills through the burning of carbon. Have you ever felt the heat and smelled the smoke coming from a burning charcoal grill? The heat and smoke are the products of a combustion reaction. Combustion is one of the five general types of chemical reactions. In this chapter, you will learn that if you can recognize a reaction as being a particular type, you may be able to predict the products of the reaction.

Classifying Reactions

The five general types of reaction are combination, decomposition, single-replacement, double-replacement, and combustion. Not all chemical reactions fit uniquely into only one category. Occasionally, a reaction may fit equally well into two categories. Nevertheless, recognizing a reaction as a particular type is useful. Patterns of chemical behavior will become apparent and allow you to predict the products of reactions.

Combination Reactions The first type of reaction is the combination, or synthesis, reaction. A **combination reaction** is a chemical change in which two or more substances react to form a single new substance. As shown in Figure 11.5, magnesium metal and oxygen gas combine to form the compound magnesium oxide.

$$2Mg(s) + O_2(g) \longrightarrow 2MgO(s)$$

Notice that in this reaction, as in all combination reactions, the product is a single substance (MgO), which is a compound. The reactants in this combination reaction (Mg and O_2) are two elements. This is often the case, but two compounds may also combine to form a single substance.

When a Group A metal and a nonmetal react, the product is a compound consisting of the metal cation and the nonmetal anion.

$$2K(s) + Cl_2(g) \longrightarrow 2KCl(s)$$

When two nonmetals react in a combination reaction, more than one product is often possible.

$$S(s) + O_2(g) \longrightarrow SO_2(g) \text{ sulfur dioxide}$$
$$2S(s) + 3O_2(g) \longrightarrow 2SO_3(g) \text{ sulfur trioxide}$$

More than one product may also result from the combination reaction of a transition metal and a nonmetal.

$$Fe(s) + S(s) \longrightarrow FeS(s) \text{ iron(II) sulfide}$$
$$2Fe(s) + 3S(s) \longrightarrow Fe_2S_3(s) \text{ iron(III) sulfide}$$

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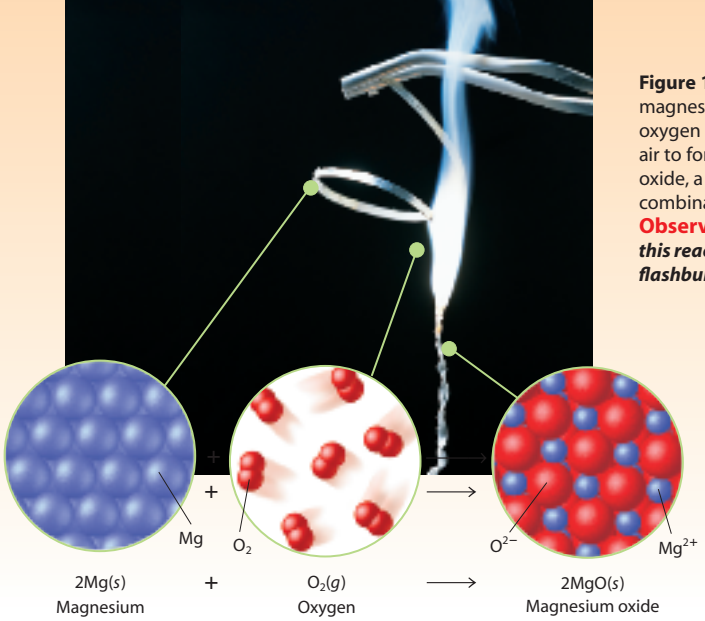

Figure 11.5 When ignited, magnesium ribbon reacts with oxygen in the surrounding air to form magnesium oxide, a white solid. This is a combination reaction.
Observing ***Why do you think this reaction was once used in flashbulbs for photography?***

CONCEPTUAL PROBLEM 11.4

Writing Equations for Combination Reactions

Copper and sulfur, shown in the photo, are the reactants in a combination reaction. Complete the equation for the reaction.

$Cu(s) + S(s) \longrightarrow$ (two reactions possible)

1 Analyze ***Identify the relevant concepts.***
Two reactions are possible because copper is a transition metal and has more than one common ionic charge (Cu^{+} and Cu^{2+}). Determine the formulas for the two products. Balance the two possible equations.

2 Solve ***Apply concepts to this situation.***
Write the skeleton equation first, then apply the rules for balancing equations.
For copper(II):
$Cu(s) + S(s) \longrightarrow CuS(s)$ (balanced)
For copper(I):
$Cu(s) + S(s) \longrightarrow Cu_2S(s)$
$2Cu(s) + S(s) \longrightarrow Cu_2S(s)$ (balanced)

Practice Problems

13. Complete and balance this equation for a combination reaction.

$Be + O_2 \longrightarrow$

14. Write and balance the equation for the formation of magnesium nitride(Mg_3N_2) from its elements.

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Problem-Solving 11.14 Solve Problem 14 with the help of an interactive guided tutorial.
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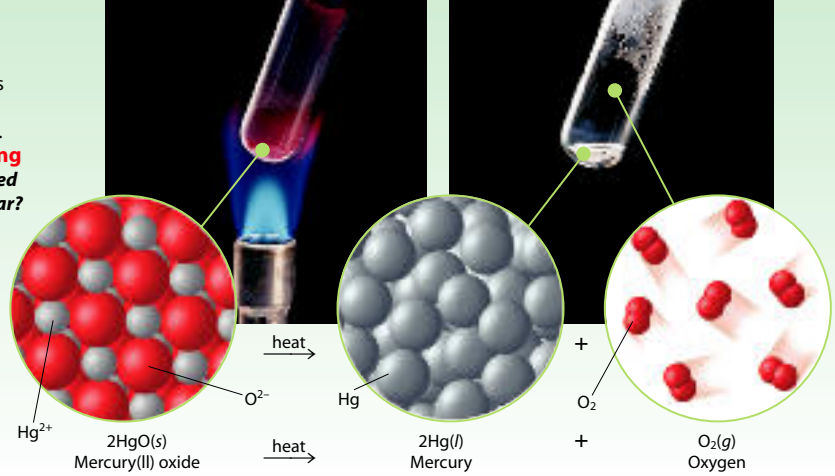
Figure 11.6 When orange-colored mercury(II) oxide is heated, it decomposes into its constituent elements: liquid mercury and gaseous oxygen.

Comparing and Contrasting ***How are the reactions pictured in Figures 11.5 and 11.6 similar? How are they different?***



Decomposition Reactions When mercury(II) oxide is heated, it decomposes or breaks down into two simpler compounds, as shown in Figure 11.6.

$$2HgO(s) \longrightarrow 2Hg(l) + O_2(g)$$

A **decomposition reaction** is a chemical change in which a single compound breaks down into two or more simpler products. Decomposition reactions involve only one reactant and two or more products. The products can be any combination of elements and compounds. It is usually difficult to predict the products of decomposition reactions. However, when a simple binary compound such as HgO breaks down, you know that the products must be the constituent elements Hg and O_2. Most decomposition reactions require energy in the form of heat, light, or electricity.

CONCEPTUAL PROBLEM 11.5

Writing the Equation for a Decomposition Reaction

Decomposition reactions that produce gases and heat are sometimes explosive, as the photo shows. Write a balanced equation for the following decomposition reaction.

$$H_2O(l) \xrightarrow{\text{electricity}}$$

1 Analyze ***Identify the relevant concepts.***
Water, a binary compound, breaks down into its elements. Balance the equation, remembering that hydrogen and oxygen are both diatomic molecules.

2 Solve ***Apply concepts to this situation.***
Write the skeleton equation, then apply the rules for balancing equations.

$$H_2O(l) \xrightarrow{\text{electricity}} H_2(g) + O_2(g)$$
$$2H_2O(l) \xrightarrow{\text{electricity}} 2H_2(g) + O_2(g) \text{ (balanced)}$$

Practice Problems

15. Complete and balance this decomposition reaction.

$$HI \longrightarrow$$

16. Write the formula for the binary compound that decomposes to the products H_2 and Br_2.

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Single-Replacement Reactions Dropping a small piece of potassium into a beaker of water creates the vigorous reaction shown in Figure 11.7. The reaction produces hydrogen gas and a large quantity of heat. The released hydrogen gas can ignite explosively.

$$2K(s) + 2H_2O(l) \longrightarrow 2KOH(aq) + H_2(g)$$

Similar but less spectacular reactions can occur. For example, if you drop a piece of zinc into a solution of copper nitrate, this reaction occurs:

$$Zn(s) + Cu(NO_3)_2(aq) \longrightarrow Cu(s) + Zn(NO_3)_2(aq)$$

These equations describe two examples of single-replacement reactions. A **single-replacement reaction** is a chemical change in which one element replaces a second element in a compound. You can identify a single-replacement reaction by noting that both the reactants and the products consist of an element and a compound. In the equation above, zinc and copper change places. The reacting element Zn replaces copper in the reactant compound $Cu(NO_3)_2$. The products are the element Cu and the compound $Zn(NO_3)_2$.

Whether one metal will displace another metal from a compound depends upon the relative reactivities of the two metals. The **activity series** of metals, given in Table 11.2, lists metals in order of decreasing reactivity. A reactive metal will replace any metal listed below it in the activity series. Thus iron will displace copper from a copper compound in solution, but iron does not similarly displace zinc or calcium.

A halogen can also replace another halogen from a compound. The activity of the halogens decreases as you go down Group 7A of the periodic table—fluorine, chlorine, bromine, and iodine. Bromine is more active than iodine, so this reaction occurs:

$$Br_2(aq) + NaI(aq) \longrightarrow NaBr(aq) + I_2(aq)$$

But bromine is less active than chlorine, so this reaction does not occur:

$$Br_2(aq) + NaCl(aq) \longrightarrow \text{No reaction}$$

Table 11.2

Activity Series of Metals

	Name	Symbol
Decreasing reactivity ↓	Lithium	Li
	Potassium	K
	Calcium	Ca
	Sodium	Na
	Magnesium	Mg
	Aluminum	Al
	Zinc	Zn
	Iron	Fe
	Lead	Pb
	(Hydrogen)	(H)*
	Copper	Cu
	Mercury	Hg
	Silver	Ag

*Metals from Li to Na will replace H from acids and water; from Mg to Pb they will replace H from acids only.

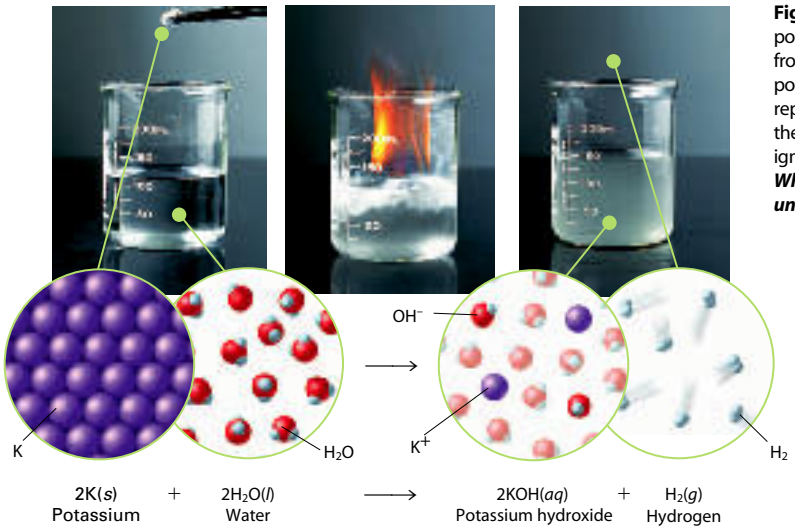

Figure 11.7 The alkali metal potassium displaces hydrogen from water and forms a solution of potassium hydroxide in a single-replacement reaction. The heat of the reaction is often sufficient to ignite the hydrogen. **Inferring** ***Why are alkali metals stored under mineral oil or kerosene?***

CONCEPTUAL PROBLEM 11.6

Writing Equations for Single-Replacement Reactions

The photo shows the reaction between $Zn(s)$ and $H_2SO_4(aq)$. Write a balanced chemical equation for each single-replacement reaction. The reactions take place in aqueous solution.

a. $Zn(s) + H_2SO_4(aq) \longrightarrow$

b. $Cl_2(aq) + NaBr(aq) \longrightarrow$

1 Analyze ***Identify the relevant concepts.***

a. According to the activity series of metals, zinc displaces hydrogen from an acid and takes its place. Balance the equation, remembering that elemental hydrogen is diatomic.

b. Chlorine is more reactive than bromine and displaces bromine from its compounds. Balance the equation. Bromine is diatomic.

2 Solve ***Apply concepts to this situation.***

Write the skeleton equation first, then apply the rules for balancing equations.

a. $Zn(s) + H_2SO_4(aq) \longrightarrow ZnSO_4(aq) + H_2(g)$ (balanced)

b. $Cl_2(aq) + NaBr(aq) \longrightarrow NaCl(aq) + Br_2(aq)$

$Cl_2(aq) + 2NaBr(aq) \longrightarrow 2NaCl(aq) + Br_2(aq)$ (balanced)

Practice Problem

17. Complete the equations for these single-replacement reactions in aqueous solution. Balance each equation. Write "no reaction" if a reaction does not occur.

a. $Fe(s) + Pb(NO_3)_2(aq) \longrightarrow$

b. $Cl_2(aq) + NaI(aq) \longrightarrow$

c. $Ca(s) + H_2O(l) \longrightarrow$

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Double-Replacement Reactions Sometimes, when two solutions of ionic compounds are mixed, nothing happens. At other times, the ions in the two solutions react. Figure 11.8 shows that mixing aqueous solutions of potassium carbonate and barium chloride results in a chemical reaction. A white precipitate of solid barium carbonate is formed. Potassium chloride, the other product of the reaction, remains in solution. This is an example of a **double-replacement reaction,** which is a chemical change involving an exchange of positive ions between two compounds. Double-replacement reactions are also referred to as double-displacement reactions. They generally take place in aqueous solution and often produce a precipitate, a gas, or a molecular compound such as water. For a double-replacement reaction to occur, one of the following is usually true.

1. One of the products is only slightly soluble and precipitates from solution. For example, the reaction of aqueous solutions of sodium sulfide and cadmium nitrate produces a yellow precipitate of cadmium sulfide.

$$Na_2S(aq) + Cd(NO_3)_2(aq) \longrightarrow CdS(s) + 2NaNO_3(aq)$$

2. One of the products is a gas. Poisonous hydrogen cyanide gas is produced when aqueous sodium cyanide is mixed with sulfuric acid.

$$2NaCN(aq) + H_2SO_4(aq) \longrightarrow 2HCN(g) + Na_2SO_4(aq)$$

3. One product is a molecular compound such as water. Combining solutions of calcium hydroxide and hydrochloric acid produces water.

$$Ca(OH)_2(aq) + 2HCl(aq) \longrightarrow CaCl_2(aq) + 2H_2O(l)$$

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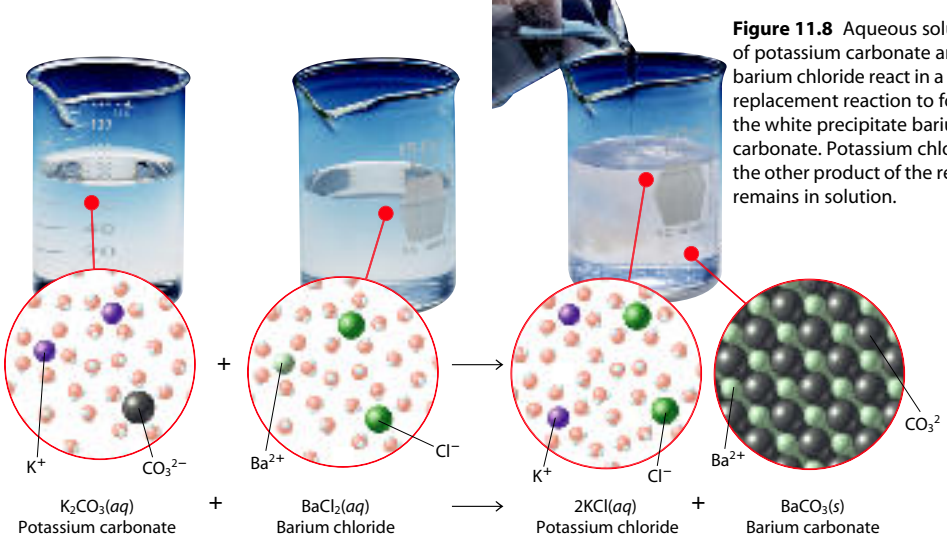

$K_2CO_3(aq)$ + $BaCl_2(aq)$ ⟶ $2KCl(aq)$ + $BaCO_3(s)$

Potassium carbonate + Barium chloride ⟶ Potassium chloride + Barium carbonate

Figure 11.8 Aqueous solutions of potassium carbonate and barium chloride react in a double-replacement reaction to form the white precipitate barium carbonate. Potassium chloride, the other product of the reaction, remains in solution.

CONCEPTUAL PROBLEM 11.7

Writing Equations for Double-Replacement Reactions

Write a balanced chemical equation for each double-replacement reaction.

a. $CaBr_2(aq) + AgNO_3(aq) \longrightarrow$ (A precipitate of silver bromide is formed.)

b. $FeS(s) + HCl(aq) \longrightarrow$ (Hydrogen sulfide gas (H_2S) is formed.)

1 Analyze ***Identify the relevant concepts.***

a. The driving force behind the reaction is the formation of a precipitate, which is shown in the photo. Write correct formulas of the products using ionic charges. Then balance the equation.

b. A gas is formed. Use ionic charges to write the correct formula of the other product. Then balance the equation.

2 Solve ***Apply concepts to this situation.***

For each reaction, write the skeleton equation first, then apply the rules for balancing equations.

a. $CaBr_2(aq) + AgNO_3(aq) \longrightarrow AgBr(s) + Ca(NO_3)_2(aq)$

$CaBr_2(aq) + 2AgNO_3(aq) \longrightarrow 2AgBr(s) + Ca(NO_3)_2(aq)$ (balanced)

b. $FeS(s) + HCl(aq) \longrightarrow H_2S(g) + FeCl_2(aq)$

$FeS(s) + 2HCl(aq) \longrightarrow H_2S(g) + FeCl_2(aq)$ (balanced)

Practice Problems

18. Write the products of these double-replacement reactions. Then balance each equation.

a. $NaOH(aq) + Fe(NO_3)_3(aq) \longrightarrow$ (Iron(III) hydroxide is a precipitate.)

b. $Ba(NO_3)_2(aq) + H_3PO_4(aq) \longrightarrow$ (Barium phosphate is a precipitate.)

19. Write a balanced equation for each reaction.

a. $KOH(aq) + H_3PO_4(aq) \longrightarrow$

b. $H_2SO_4(aq) + Al(OH)_3(aq) \longrightarrow$

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Problem-Solving 11.18 Solve Problem 18 with the help of an interactive guided tutorial.

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Combustion Reactions The flames of a campfire or a gas grill are evidence that a combustion reaction is taking place. A **combustion reaction** is a chemical change in which an element or a compound reacts with oxygen, often producing energy in the form of heat and light. A combustion reaction always involves oxygen as a reactant. Often the other reactant is a hydrocarbon, which is a compound composed of hydrogen and carbon. The complete combustion of a hydrocarbon produces carbon dioxide and water. But if the supply of oxygen is limited during a reaction, the combustion will not be complete. Elemental carbon (soot) and toxic carbon monoxide gas may be additional products. The complete combustion of a hydrocarbon releases a large amount of energy as heat. That's why hydrocarbons such as methane (CH_4), propane (C_3H_8), and butane (C_4H_{10}) are important fuels. The combustion reaction for methane is shown in Figure 11.9. Gasoline is a mixture of hydrocarbons that can be approximately represented by the formula C_8H_{18}. The complete combustion of gasoline in a car engine is shown by this equation.

$$2C_8H_{18}(l) + 25O_2(g) \longrightarrow 16CO_2(g) + 18H_2O(l)$$

The reactions between oxygen and some elements other than carbon are also examples of combustion reactions. For example, both magnesium and sulfur will burn in the presence of oxygen. As you look at these combustion equations, notice that the reactions could also be classified as combination reactions.

$$2Mg(s) + O_2(g) \longrightarrow 2MgO(s)$$

$$S(s) + O_2(g) \longrightarrow SO_2(g)$$

Checkpoint ***What are the products of the combustion of a hydrocarbon?***

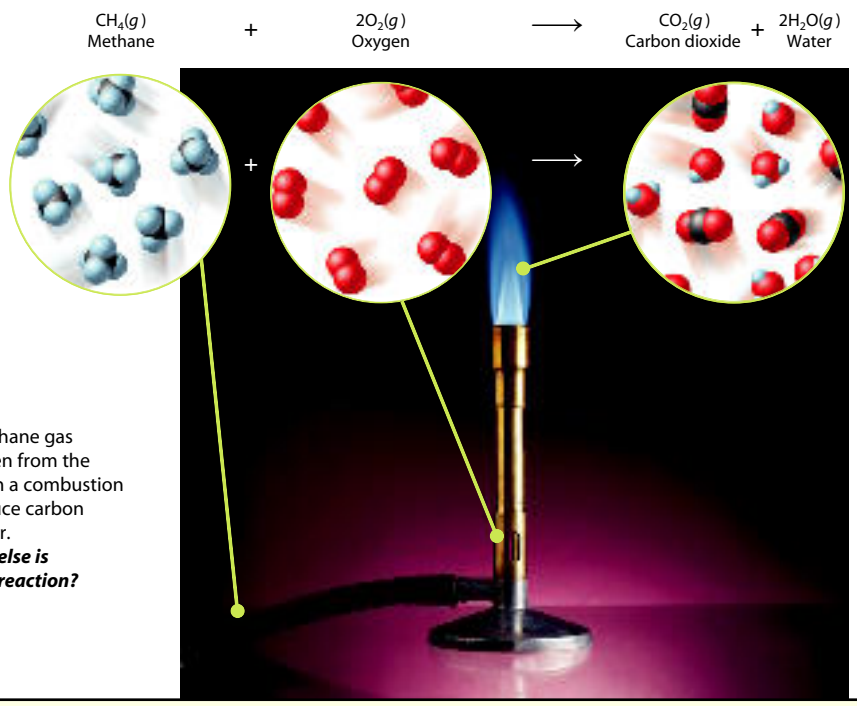

Figure 11.9 Methane gas reacts with oxygen from the surrounding air in a combustion reaction to produce carbon dioxide and water.
Inferring ***What else is produced in this reaction?***

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CONCEPTUAL PROBLEM 11.8

Writing Equations for Combustion Reactions

An alcohol lamp often uses ethanol as its fuel. Write balanced equations for the complete combustion of these compounds.

a. benzene ($C_6H_6(l)$) **b.** ethanol ($CH_3CH_2OH(l)$)

1 Analyze ***Identify the relevant concepts.***
Oxygen is the other reactant in these combustion reactions. The products are CO_2 and H_2O. Write the skeleton equation for each reaction, then balance the equation.

2 Solve ***Apply concepts to this situation.***
For each reaction, write the skeleton equation, then apply the rules for balancing equations.

a. $C_6H_6(l) + O_2(g) \longrightarrow CO_2(g) + H_2O(g)$
$2C_6H_6(l) + 15O_2(g) \longrightarrow 12CO_2(g) + 6H_2O(g)$ (balanced)

b. $CH_3CH_2OH(l) + O_2(g) \longrightarrow CO_2(g) + H_2O(g)$
$CH_3CH_2OH(l) + 3O_2(g) \longrightarrow 2CO_2(g) + 3H_2O(g)$ (balanced)

Practice Problems

20. Write a balanced equation for the complete combustion of each compound.
a. formic acid (HCOOH)
b. heptane (C_7H_{16})

21. Write a balanced equation for the complete combustion of glucose ($C_6H_{12}O_6$).

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Problem-Solving 11.21
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Predicting the Products of a Chemical Reaction

Now that you have learned about some of the basic reaction types, you can predict the products of many reactions. **The number of elements and/or compounds reacting is a good indicator of possible reaction type and thus possible products.** For example, in a combination reaction, two or more reactants (elements or compounds) combine to form a single product. In a decomposition reaction, a single compound is the reactant; two or more substances are the products. An element and a compound are the reactants in a single-replacement reaction. A different element and a new compound are the products. In a double-replacement reaction, two ionic compounds are the reactants; two new compounds are the products. The reactants in a combustion reaction are oxygen and usually a hydrocarbon. The products of most combustion reactions are carbon dioxide and water.

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Simulation 12 Practice classifying reactions according to reaction type.
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Figure 11.10 The five types of chemical reactions discussed in this chapter are summarized here.

1 Combination Reaction

General Equation: $R + S \longrightarrow RS$

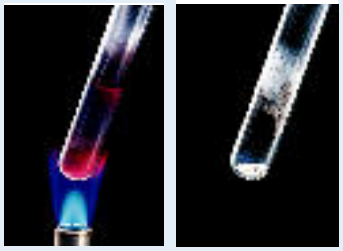
Reactants: Generally two elements, or two compounds (where at least one compound is a molecular compound)
Probable Products: A single compound
Example: Burning magnesium in air

$2Mg(s) + O_2(g) \longrightarrow 2MgO(s)$

2 Decomposition Reaction

General Equation: $RS \longrightarrow R + S$

Reactants: Generally a single binary compound or a compound with a polyatomic ion
Probable Products: Two elements (for a binary compound), or two or more elements and/or compounds (for a compound with a polyatomic ion)
Example: Heating mercury(II) oxide



$2HgO(s) \longrightarrow 2Hg(l) + O_2(g)$

3 Single-Replacement Reaction

General Equation: $T + RS \longrightarrow TS + R$

Reactants: An element and a compound
In a single-replacement reaction, an element replaces another element from a compound in aqueous solution. For a single-replacement reaction to occur, the element that is displaced must be less active than the element that is doing the displacing.
Probable Products: A different element and a new compound
Example: Potassium in water

$2K(s) + 2H_2O(l) \longrightarrow 2KOH(aq) + H_2(g)$

4 Double-Replacement Reaction

General Equation: $R^+S^- + T^+U^- \longrightarrow R + U^- + T^+S^-$

Reactants: Two ionic compounds
In a double-replacement reaction, two ionic compounds react by exchanging cations to form two different compounds.
Probable Products: Two new compounds
Double-replacement reactions are driven by the formation of a precipitate, a gaseous product, or water.
Example: Reaction of aqueous solutions of barium chloride and potassium carbonate

$K_2CO_3(aq) + BaCl_2(aq) \longrightarrow 2KCl(aq) + BaCO_3(s)$

5 Combustion Reaction

General Equation: $C_xH_y + (x + y/4)\,O_2 \longrightarrow xCO_2 + (y/2)H_2O$

Reactants: Oxygen and a compound of C, H, (O)
When oxygen reacts with an element or compound, combustion may occur.
Probable Products: CO_2 and H_2O
With incomplete combustion, C and CO may also be products.
Example: The combustion of methane gas in air

$CH_4(g) + 2O_2(g) \longrightarrow CO_2(g) + 2H_2O(g)$

11.2 Section Assessment

22. **Key Concept** What are the five types of chemical reactions?

23. **Key Concept** What are the keys to predicting the products of the five general types of reactions?

24. Classify each reaction and balance the equations.
- **a.** $C_3H_6 + O_2 \longrightarrow CO_2 + H_2O$
- **b.** $Al(OH)_3 \longrightarrow Al_2O_3 + H_2O$
- **c.** $Li + O_2 \longrightarrow Li_2O$
- **d.** $Zn + AgNO_3 \longrightarrow Ag + Zn(NO_3)_2$

25. Which of the five general types of reaction would most likely occur, given each set of reactants? What are the probable products?
- **a.** an aqueous solution of two ionic compounds
- **b.** a single compound
- **c.** two elements
- **d.** oxygen and a compound of carbon and hydrogen

26. Complete and balance an equation for each reaction.
- **a.** $CaI_2 + Hg(NO_3)_2 \longrightarrow$ (HgI_2 precipitates.)
- **b.** $Al + Cl_2 \longrightarrow$
- **c.** $Ag + HCl \longrightarrow$
- **d.** $C_2H_2 + O_2 \longrightarrow$
- **e.** $MgCl_2 \longrightarrow$

27. What are the three types of products that result from double-replacement reactions?

Connecting Concepts

Molecular Compounds Hydrogen peroxide is an antiseptic that undergoes a decomposition reaction in the presence of living cells. Refer to Section 8.1 and write a paragraph giving evidence that hydrogen peroxide is a molecular compound.

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Assessment 11.2 Test yourself on the concepts in Section 11.2.

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Technology & Society

Combating Combustion

A fire has three requirements: oxygen, fuel, and a temperature high enough to initiate and sustain combustion. Firefighters put out fires by eliminating one or more of these requirements. When water is sprayed on a typical building fire, it stops the fire by lowering the temperature of the burning material and soaking it with noncombustible water. Steam from the vaporizing water also tends to displace air from around the fuel, which denies oxygen to the fuel. To improve the ability of water to saturate the fuel, for example, upholstered furniture and rugs, a substance called a surfactant is added to the water. **Inferring** ***How can it help to roll on the ground if your clothes are on fire?***

Water Water is the most important tool for firefighters. Water-based foams are more effective, but they are also more expensive.

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Forest fires Firefighters combat forest fires from the air by spreading substances that coat the surfaces of the trees to prevent burning. They can also cut the fire off from its fuel by using bulldozers to cut a clear path through the trees or by setting a controlled blaze.

Grease fires Water sprayed on a grease fire can spread the flames. A carbon-dioxide fire extinguisher produces a cloud of heavier-than-air CO_2 that blankets the fire and cuts off the oxygen supply.

Electrical fires Chemicals such as monoammonium phosphate (MAP), blown from a dry-chemical extinguisher, cover an electrical fire and cut off oxygen.